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SIMULATION OF INDIVIDUAL THERMOREGULATORY RESPONSES TO PARTIAL COLD WATER IMMERSION AND EXERCISE

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Introduction

During emergencies, adventure racing or military operations, individuals may be partially submerged in cold water, thereby at risk for rapid heat loss and hypothermia. By modeling the effects of water immersion, this hazard may be better understood, and more active preventive measures can be implemented or public warnings issued. The purpose of this study was to determine whether a previously validated cold thermoregulatory model (CTM) (1,2) for predicting temperature responses in sedentary people during whole-body immersion was applicable to partial immersion in cold water during exercise (treadmill walking).

Methods

CTM is a six cylinder mathematical model representing the head, trunk, arms, legs, hands, and feet. Each segment is further concentrically divided into compartments representing the core, muscle, fat, and skin. The integrated thermal signal to the thermoregulatory controller is composed of the weighted thermal input from thermal receptors at various sites distributed throughout the body. The difference between this signal and its threshold activates several thermoregulatory actions including vasomotor changes, sweat production and metabolic heat production. The shivering thermogenesis function (i.e. part of metabolic heat production) includes shivering exhaustion, intensity control, maximal capability, and inhibition due to a low core temperature.

Two subjects, whose physical characteristic are listed in Table 1, were immersed in 10 and 15°C water at both the chest (CH) and waist level (WA). They wore a standard US military uniform (BDU) for all trials and walked at 0.44 m·s⁻¹ until their rectal temperature (T_{re}) fell to 35.5°C or they requested to stop. A CTM simulation was run for each of the 8 individual trials (abbreviated as CH15, CH10, WA15, and WA10).

Table 1 Individual physical characteristics for two subjects

Subject	age (year)	height (m)	weight (kg)	fat percentage (%)	VO ² max (ml/min kg)
A	20	1.75	69.0	17.0	42.5
B	18	1.73	68.0	15.0	47.8

The CTM inputs were the individual characteristics listed in Table 1 plus environmental parameters (i.e. temperature, humidity and wind velocity) and clothing parameters (clo, Im) for each of the six cylinders. Since only a portion of the torso was submersed in CH and WA, the environmental and clothing parameters for the torso were modified. It was assumed that 20% of the torso was exposed to air while 80% was immersed during CH, whereas during WA, 80% of the torso was exposed to air while 20% was immersed. In addition, measured heat transfer coefficients for trials, instead of model default values, were used to make the simulation more realistic. The measured core temperature (T_c , esophageal temperature T_{es} , and rectal temperature) and mean skin temperature (T_{sk} , 7 sites) were compared with the predicted T_c and the T_{sk} , respectively, using root mean square deviations (RMSD) (3,4). RMSD was calculated between the observed and predicted temperatures with a 5 min interval.

Results and Discussion

Calculated RMSD indicates that the measured T_c agreed with predicted T_c for both subjects (Table 2). However, the predicted T_{sk} was close to the measured T_{sk} for Subject A, but not for Subject B, as shown by relatively high RMSDs. The differences are due to initial T_{sk} values; predicted T_{sk} started always at a thermal neutral temperature of 33°C while the measured T_{sk} began at ~24-26°C. Figure 1 shows the predicted and

measured T_c for Subject A and B during CH15, CH10, WA15 and WA10. While predicted T_c agree with measured T_c during CH15 and CH10, predicted T_c are higher than measured T_c during WA. The clothing covering the torso was getting wet during WA, the water in the fabric evaporated and then enhanced evaporative heat loss to the environments. This extra heat loss was not taken into account in the simulation. Physiological responses to partial immersion were also complicated. As shown in Fig.1 for subject A, differences between the measured T_c at the end of CH10 and WA10 trials were minimal. Given that the prediction was run for an individual response rather than a group response, CTM was able to simulate T_c in non-uniform environments (partial immersion, walking) with reasonable accuracy.

Table 2 RMSD of the core and mean skin temperatures for subjects A and B

	Subject A		Subject B	
	T_c	T_{sk}	T_c	T_{sk}
CH10	0.25	1.10	0.15	2.37
CH15	0.26	0.82	0.09	1.45
WA10	0.21	1.40	0.17	2.39
WA15	0.13	1.05	0.23	2.66

Partial immersion represents a relatively complex set of experimental conditions. Although CTM allows each of the six cylinders to have its own environmental and clothing parameters, in this experiment, one cylinder (e.g., torso) is only partially immersed. To adapt the model for partial immersion, adjustments based on the percentage of the cylinder that was immersed as well as using the actual convective heat coefficient were made to the inputs for the torso section. Results from this study indicate that adjustments (i.e. parameters for the torso section) to the model based on best available information are necessary to ensure that the inputs and predictions more accurately represent actual conditions.

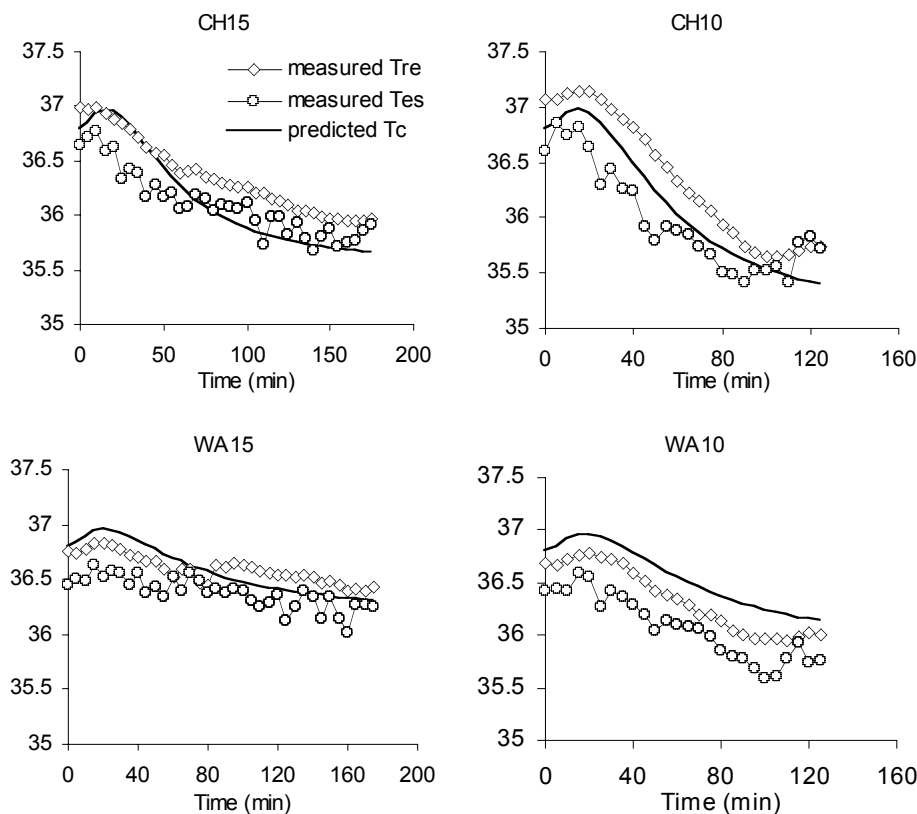


Figure 1 Subject A, measured and predicted T_c during CH15, CH10, WA15, and WA10

When CTM is used to predict thermal responses in the field, it is important to use the best available parameters as inputs. To ensure that the inputs are realistic, rigorous evaluation to identify all possible scenarios is required. To provide the most accurate predictions, it may be necessary to have real-time monitoring of the conditions so that input parameters can be adjusted accordingly. When the information available is limited, it might be necessary to run thermal response simulations for the worst and best cases. If applied appropriately, models such as CTM could help to plan operations, organize rescue activities, assist post mortem investigations, etc.

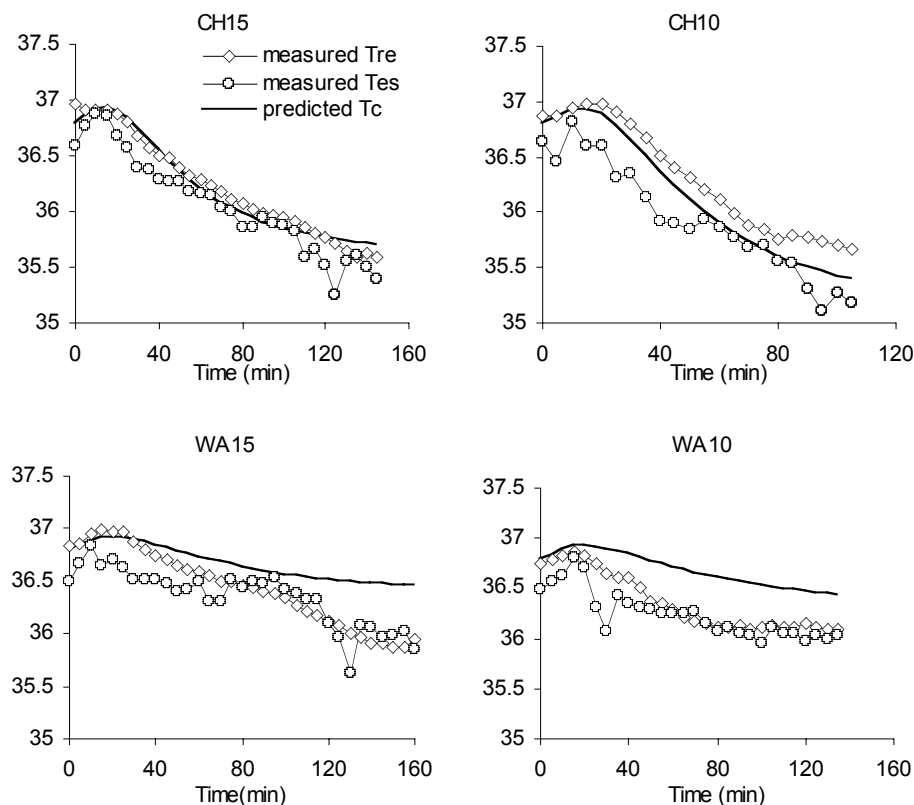


Figure 2 Subject B, measured and predicted Tc during CH15, CH10, WA15, and WA10

Conclusions

These results demonstrate that the CTM can reasonably simulate core temperature responses to partial water immersion during exercise. However, to obtain more accurate core and skin temperature predictions, it is critical to determine the appropriate parameter inputs for each body segment before running the simulation.

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